

Areal distribution and age of low-K, high-alumina olivine tholeiite magmatism in the northwestern Great Basin

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ABSTRACT

Field, petrographic, chemical, and geochronologic information has led to the identification and characterization of a widespread low-K, high-alumina olivine tholeiite (HAOT) magma type in the northwestern Great Basin. This basalt covers at least 22,000 km² and is estimated to represent a total volume of at least 650 km³.

The time period over which HAOT lavas were erupted extends from late Miocene to Holocene (10.5–0 m.y. B.P.). This interval overlaps with the timing of Snake River, Cascade, and northwestern Basin and Range volcanism but distinguishes HAOT from the main pulse of Columbia River volcanism (~15 m.y. B.P.). Furthermore, three major pulses of HAOT magmatism are suggested from the geochronology of this study: 0 to 2.5 m.y. B.P., 3.5 to 6 m.y. B.P., and 7 to 10 m.y. B.P.

The distinctive holocrystalline, nonporphyritic, and diktytaxitic texture, the low incompatible-element concentrations, and the high MgO/FeO* of HAOT serve to distinguish this basalt from other basalts of the northwestern United States. The low incompatible-element signature accentuates the similarities between HAOT, mid-ocean-ridge basalts, and back-arc-basin basalts. These similarities, combined with the HAOT chronology, support the idea that the processes giving rise to extensional tectonism and HAOT magmatism in the northwestern Great Basin are similar to those acting in active back-arc-spreading regions.

INTRODUCTION

The late Cenozoic geologic history of the western United States has been dominated by voluminous volcanism associated with the Columbia, Snake River, Basin and Range, and Cascade provinces. Much of this activity, including the andesitic volcanism of the Cascades and the basalt-rhyolite volcanism of the Basin and Range, has been linked to tectonic processes occurring along the Pacific–North American Plate boundaries (Atwater, 1970; Christiansen and Lipman, 1972; Christiansen and McKee, 1978). The tectonic significance of the Columbia Plateau and Snake River Plain is less well defined, although the volcanism associated with these two regions presumably must also be somehow related to Pacific–North American plate interactions.

As a first step toward understanding the interrelationships of the individual volcanic provinces, we have chosen to study the late Cenozoic volcanic assemblages of the northwestern Great Basin region of the western Cordillera (Fig. 1). Of particular interest is a widespread low-K, high-alumina olivine tholeiite (HAOT) that is encountered throughout the enclosed region in Figure 1. This HAOT is unique to this geographic area and displays many chemical similarities to ocean-ridge tholeiites and back-

arc-basin basalts. Flows of this magma type and associated basalts have been included in various formations of local importance such as the Mesa Basalt (Wheeler and Coombs, 1967), the Warner Basalt (Powers, 1932; Anderson, 1941; and many others), and the Banbury Basalt (Malde and Powers, 1962; Stewart and Carlson, 1976). Other workers have included flows of HAOT in larger-scale groupings such as the "Basalts of South-eastern Oregon" (Leeman and Rogers, 1970), late Miocene–Pliocene basalts of southeastern Oregon (Walker, 1970), and high-alumina basalts of the Oregon Plateau (Waters, 1962). To our knowledge, no one has conducted a detailed regional petrologic-geochronologic study of this HAOT, even though many researchers include analyses of it in their work. The only available K–Ar data in the literature (Evernden and others, 1964; Coe, 1967; Walker and Swanson, 1969; Mertzman, 1977a; Zebback and Thompson, 1978; and McKee and others, 1983) are also of a comparative nature and do not focus solely on the importance of the HAOT.

The purpose of this paper is to define the geochemical nature and to delineate the geographic distribution, volume, and geochronology of HAOT. Petrographic, geochemical, and K–Ar geochronologic data are presented for HAOT, and for spatially associated evolved tholeiites (transitional basalts, TB) and alkaline olivine basalts (AOB). Basalts, basaltic andesites, and more silicic rocks from provinces surrounding and intercalating with the northwestern Great Basin are also examined in order to better understand the relationships between these units and HAOT. Interpretations and discussions are based on ~200 new major- and trace-element analyses and 90 K–Ar age determinations. A brief discussion of the K–Ar analytical procedures is presented in the Appendix. The reader is referred to Hart (1982) for detailed discussions of the geochemical procedures as well as detailed petrographic descriptions of all analyzed samples.

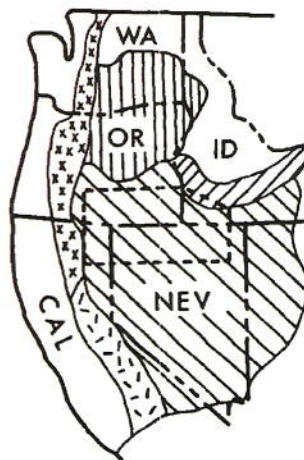


Figure 1. Important igneous provinces of the northwestern United States. The region enclosed by dashed lines is discussed in this paper and is shown in more detail in Figure 2.

- GREAT BASIN
- COLUMBIA PLATEAU
- SNAKE R. PLAIN
- CASCADES
- SIERRA NEV.

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Additional tabular material for this article may be secured by requesting Supplementary Data 84-3 from the GSA Documents Secretary.

BACKGROUND

The area of study (Figs. 1 and 2) encompasses approximately 150,000 km² of volcanic terrain between 41°N to 44°N lat. and 114°W to 122°W long. in the northwestern Great Basin. This is a structurally complex region characterized by large north-south-trending normal faults as well as a belt of west-northwest-trending right-lateral strike-slip fault zones (Walker Lane System), best defined by the Brothers Fault Zone of southeastern Oregon (Higgins, 1973; Lawrence, 1976). These structures are probably the surface expressions of regional east-west extension during late Cenozoic time (Zoback and Thompson, 1978; Livaccari, 1979). Absolute extension may range from 50 to 200 km (Lawrence, 1976), with a total amount of right-lateral displacement along the Walker Lane System of as much as 190 km (Stewart and others, 1968).

The upper Cenozoic geology of this region is characterized by voluminous tholeiitic basalts and silicic ash-flow tuffs and subordinate alkaline olivine basalts. The most widespread variety of tholeiite is HAOT, with significant accumulations near the eastern and western margins of the study area. In northeastern California, HAOT interfingers with calc-alkaline lavas of the southern Cascades (Smith and Carmichael, 1968) and basaltic to silicic volcanics of the Medicine Lake–Lava Beds National Monument area (Mertzman, 1977a, 1977b, 1981). These lavas together constitute much of what is referred to as the Modoc Plateau (Powers, 1932). Throughout most of south-central Oregon, HAOT is closely associated with silicic lavas and ash flows, alkaline basalts, and basalts of Steens Mountain and/or Steens–Columbia River affinity (Hart and Mertzman, 1982). In the Oregon–Idaho–Nevada border region, hereinafter referred to as the Owyhee River–Western Snake River Plain (OR–WSRP) region, a complex sequence of igneous and sedimentary material is observed. Dominating the pre-Miocene to Miocene record are mineralized silicic volcanic and plutonic rocks of the Owyhee and Jarbidge–Independence Mountains (Coats, 1964; Pansze, 1975; Bennett, 1976). Miocene to Pliocene alkaline basalts and rhyolites typical of the Basin and Range basalt-rhyolite association are also present (Christiansen and Lipman, 1972). The late Miocene to Holocene record is characterized by interbedded basalts, silicic tuffs, breccias, and flows and by lacustrine sediments historically considered as part of the Snake River volcanic province

(see Armstrong and others, 1975, for reference summary). Zero- to 2-m.y.-old alkaline olivine basalts are observed only in the Jordan Valley area. The dominant rock type in this region is tholeiitic basalt, including chemically distinct varieties such as HAOT and Snake River olivine tholeiite (SROT). Underlying the basaltic sequence is a sequence of nonmineralized silicic flows and welded-vitric tuffs originally defined by Malde and Powers (1962) as the Idavada volcanics.

The basalts of the northwestern Great Basin probably are the products of scattered fissure and fissure-controlled centralized eruptions triggered by intense extensional tectonism. In southern Oregon, the presence of some north-south-trending dikes together with a general north-south alignment of small individual eruptive centers supports this suggestion.

PETROGRAPHY AND ELEMENTAL GEOCHEMISTRY

Introduction

Inasmuch as the main purpose of this paper is to define the characteristics of HAOT, we limit detailed petrographic and chemical descriptions to only HAOT and closely associated olivine tholeiites from the OR–WSRP region. These tholeiites have been subdivided into the following four distinct groups on the basis of their concentrations of K₂O and TiO₂: HAOT (K₂O ≤ 0.39% and TiO₂ ≤ 1.35%); low-K, low-Ti transitional tholeiites (LKLT; K₂O ≤ 0.5% and TiO₂ ≤ 2.0%); low-K, high-Ti transitional tholeiites (LKHT; K₂O ≤ 0.5% and TiO₂ > 2.0%); and high-K, high-Ti tholeiites (K₂O > 0.5% and TiO₂ > 2.0%). The last group is representative of, and referred to as, Snake River Plain olivine tholeiites (SROT). The cutoff points for this classification are based on histograms of K₂O and TiO₂ abundance in the samples. The chemical characteristics of northwestern Great Basin alkaline olivine basalts are presented only for comparison and will be discussed in greater detail elsewhere.

Petrography

The HAOTs range from light to medium gray with distinctive non-porphyrific, diktytaxitic textures. Olivine is usually present as subhedral to anhedral intergranular 0.2 to 1.5 mm microphenocrysts. Some samples contain scattered 3-mm-long olivine phenocrysts. Combining limited electron microprobe data and optical characteristics yields a composition of Fo_{68–72}. This olivine, generally composing approximately 25% of the rock, is seen to have undergone varying degrees of alteration to red-brown iddingsite, and in some cases to iron oxide. Augitic clinopyroxene is the only pyroxene phase present and is subordinate to both olivine and plagioclase. Plagioclase ranges from <0.5 mm to >3 mm in length and is both clear and partially resorbed. Compositions of An₆₀ to An₇₅ are most common, with normal zoning observed in some larger grains. The plagioclase and cpx typically form subophitic to ophitic intergrowths and some samples also exhibit intergranular patches of olivine and oxide. Cr-spinel is frequently present as small anhedral grains poikilitically enclosed in olivine. Interstitial phases include Fe-Ti oxide, oxide-rich microcrystalline material, glass and minor apatite, and calcite-clay. Although generally equigranular and nonporphyritic, some samples do contain glomeroporphyritic clusters of plagioclase and olivine.

The LKLT, LKHT, and SROT samples possess the same basic mineralogies as do the HAOTs but exhibit significant textural variations highlighted by porphyritic and/or glomeroporphyritic plagioclase and olivine. Intergranular to intersertal textures are as common as subophitic and ophitic textures. Diktytaxitic varieties are less abundant, progressing

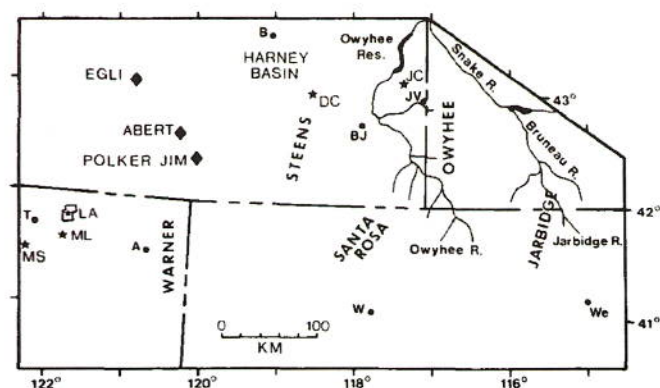


Figure 2. Detailed map of study area showing major rivers, mountain ranges, fault rims (◆), volcanic centers (★; JC = Jordan Craters, DC = Diamond Craters, LA = Lava Beds National Monument, ML = Medicine Lake, MS = Mount Shasta), and towns (•; A = Alturas, B = Burns, BJ = Burns Junction, JV = Jordan Valley, T = Tennant, W = Winnemucca, We = Wells) discussed in the text.

from LKLT to SROT. Highly iddingsitized olivine is present from ground-mass grains (<0.5 mm) to phenocrysts >3 mm in length. In the LKLT samples, a range in cpx compositions from augite to titanite is observed, but titanite is by far the dominant pyroxene in the LKHT and SROT samples. Other ophitic samples display individual cpx grains as large as 2 mm. For the most part, olivine and cpx are observed in nearly equal proportions. Plagioclase occurs as clear to partially resorbed microlites, laths, and phenocrysts ranging from <0.3 mm to >4 mm in length and from An₄₅ to An₇₂ in composition. Both normal zoning and reverse zoning are noted. Fe-Ti oxide also occurs as microphenocrysts and phenocrysts in some of the LKHT and SROT samples. In addition to the interstitial phases noted for the HAOTs, many of the LKHT and SROT lavas contain a microcrystalline phase rich in cpx, oxide, and glass. This phase may represent either a late-stage alteration of cpx to oxide or mesostasis. Increased amounts of secondary matrix alteration such as clay, calcite, and chalcedony are also characteristic of these samples.

The textural variations together with cpx composition and the occurrence of Fe-Ti oxide as a phenocryst phase allow for straightforward distinction between HAOT and the LKHT and SROT lavas. The petrographic characteristics of the HAOTs set these basalts apart from other important basalts of the northwestern United States. For comparison, a summary of basalt modal mineralogies is presented in Table 1. Furthermore, the HAOTs display rather uniform petrographic characteristics over their entire outcrop area.

TABLE 1. COMPARISON OF BASALT MODES

(n)	HAOT 20	SROT 150	BY 33	CRB 144	BRAB 51
Plag.	46.96	51.4	54.6	37.5	46
Olivine	23.94	13.7	13.6	2.8	13
Cpx	20.45	16.8	18.5	30.7	26
Oxide	6.10	5.2	3.8	7.5	6
Glass/matrix	2.65	13.9	9.3	18.0	8
Other				3.5	

Note: all data from compilation in Hart (1982) SROT, Snake River olivine tholeiites; BY, Banbury basalt; CRB, Columbia River basalts; BRAB-Basin and Range alkaline basalts.

TABLE 2. AVERAGE MAJOR- AND TRACE-ELEMENT DATA

(n)	HAOT 50	LKLT 32	LKHT 11	SROT* 18	AOB† 20
SiO ₂	47.66	47.29	46.82	45.76	48.09
TiO ₂	1.00	1.68	2.23	2.99	2.09
Al ₂ O ₃	16.91	16.02	15.47	15.12	16.40
Fe ₂ O ₃	2.97	3.44	3.63	4.38	3.17
FeO	7.18	8.07	9.31	9.83	7.24
MnO	0.17	0.18	0.19	0.21	0.17
MgO	9.06	8.20	8.23	7.10	7.10
CaO	11.20	10.90	10.34	9.83	9.31
Na ₂ O	2.53	2.44	2.24	2.29	3.26
K ₂ O	0.23	0.36	0.37	0.66	1.17
P ₂ O ₅	0.13	0.28	0.37	0.60	0.40
L.O.I.	0.84	1.08	1.18	1.62	0.71
Total	99.88	99.94	100.38	100.39	99.11
FeO*	9.88	11.20	12.61	14.05	10.12
MgO/FeO*	0.92	0.73	0.65	0.51	0.70
Rb	2.1	7.3	4.6	5.8	20
Sr	255	246	253	327	514
Ni	154	130	115	85	95
Ba	141	253	348	348	386
Zr	95	140	177	275	226
V	191	230	276	321	221
Y	20	24	30	38	21
K/Rb	909	409	668	944	486
Rb/Sr	0.008	0.030	0.018	0.018	0.039

Group designations as explained in the text. L.O.I. = total loss on ignition, FeO* = total Fe as FeO.

*Trace, FeO, Fe₂O₃, and L.O.I. averages based on 10 analyses.

†Trace averages based on 15 analyses.

Major- and Trace-Element Chemistry

The majority of the basalts analyzed for this study fall into the previously defined groups. Considering the total alkali versus silica content and the normative mineralogy of these lavas, it is apparent that they are predominantly olivine tholeiites. The high concentration of Al₂O₃ (>16 wt %) in many of these basalts indicates that they best be referred to as high-alumina olivine tholeiites (HAOT). The average major- and trace-element characteristics for the HAOT, LKLT, LKHT, and SROT lavas are given in Table 2. Also listed is the average of analyses performed on AOBs associated with these tholeiites. Significant elemental variations exist between the olivine tholeiites. These variations are particularly large and rather uniform for MgO, FeO, and the incompatible or large ionic lithophile elements (LILE). MgO and FeO behave conversely in these lavas and their abundances, together with the calculated MgO/FeO* ratios, are good indicators of the relative degree of fractionation a particular lava has undergone (Saunders and Tarney, 1979). The HAOTs are the least fractionated and lowest LILE (collectively referred to as primitive) lavas sampled. A range in Mg number [$\text{Mg}/(\text{Mg} + \text{Fe}^{2+}) \times 100$; atomic] from 65 to 71 is observed in these basalts, which could indicate equilibrium with upper-mantle olivines, assuming $\text{K}_{\text{olivine/liq}}^{\text{Fe}^{2+}/\text{Mg}} \geq 0.3$ (Irving, 1978). The maximum Ni content of any of the HAOTs is 216 ppm, which is slightly lower than the minimum value of 237 ppm suggested by Sato (1977) to represent primary unfractionated basaltic magma. Even those HAOTs with Mg numbers >70 thus may have undergone small amounts of olivine fractionation. The HAOTs also display depleted LILE signatures (K₂O ~0.09% to 0.39%; TiO₂ ~0.7% to 1.35%; Rb <1–6 ppm; Zr ~50–160 ppm) and high abundances of CaO (~10% to 12.5%) and of Al₂O₃ (>15.5% to 18%). A gradual increase in incompatible-element and FeO* abundances coupled with a decrease in MgO, Ni, and CaO occurs from primitive HAOT to more evolved SROT. These systematic elemental variations may best be explained by mixing between two chemically distinct upper-mantle source regions (Hart and Mertzman, 1981).

A very important characteristic of the HAOT lavas is their regional chemical homogeneity. This point is well illustrated in Figure 3, where percent K₂O, percent TiO₂, ppm Rb, and ppm Ba are plotted versus longitude across the northwestern Great Basin. The HAOTs plotted in this figure range from 0 to 10.5 m.y. in age regardless of chemistry or location. Such chemical homogeneity is unusual in continental flood basalts (Lee-man and Rogers, 1970).

For comparative purposes, the HAOT, LKLT, LKHT, and SROT data from this study are plotted on a MgO-TiO₂-K₂O ternary diagram (Fig. 4). The systematic elemental variation from HAOT to SROT is again noted. Also plotted on this figure are fields for northwestern Great Basin AOBs, Columbia River Basalts, and Steens Mountain Basalts. Further comparisons are made between HAOT and other continental and oceanic basalts on the basis of average chemical characteristics as summarized in Table 3. It is obvious from both Figure 4 and Table 3 that HAOT is considerably more primitive than other basalts from the western United States. For example, the average MgO/FeO* ratio for HAOT is 0.93, compared to 0.79, 0.78, 0.59, and 0.57 for the Albuquerque tholeiitic volcanoes, average Basin and Range alkaline basalts, average Snake River olivine tholeiites, and Columbia River-high-Mg Picture Gorge Basalt, respectively. A striking similarity is seen among the average compositions of HAOT, mid-ocean-ridge basalt (MORB), and back-arc-basin basalts (BABB). A range in MORB compositions from extremely LILE-depleted (6 ppm Rb, 600 ppm K, TiO₂ <1%) to more enriched varieties (7 ppm Rb, 3,600 ppm K, TiO₂ >1%) has been reported (Sun and others, 1979). Similar elemental variation is observed in HAOT. Compositionally similar basalts are also erupted in extensional regions behind many island arcs

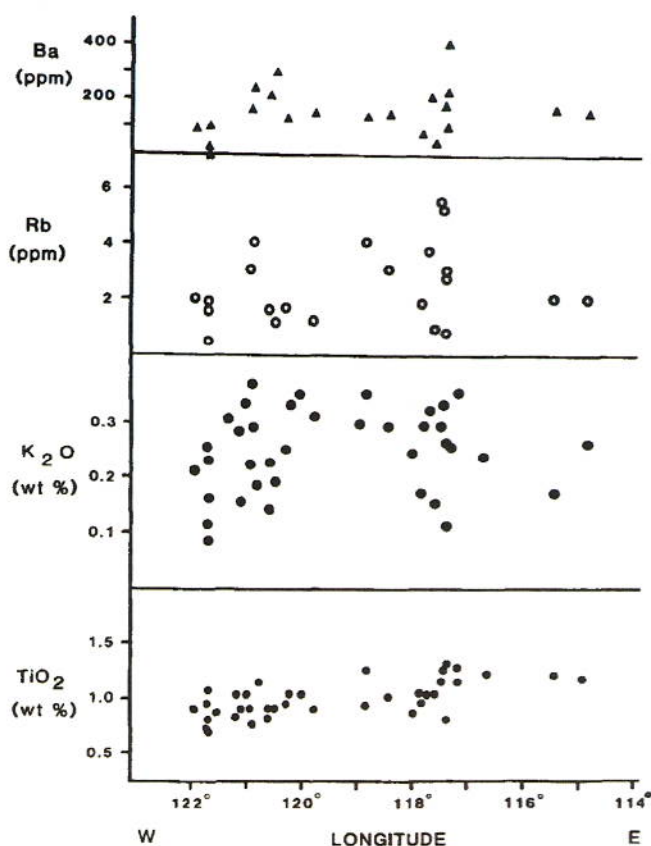


Figure 3. Plot of Ba, Rb, K₂O, and TiO₂ concentrations in HAOT versus longitude across the northwestern Great Basin.

(for example, Lau Basin, Hawkins, 1976; East Scotia Sea, Saunders and Tarney, 1979). The most significant differences between HAOT and these other two basalt types are the higher abundances of both Sr and Ba in HAOT (255 ppm and 141 ppm, respectively) than in MORB (118 ppm and 27 ppm, respectively) and BABB (214 ppm and 79 ppm, respectively) (data from compilation in Hart, 1982). Although some HAOTs are depleted in these elements (Ba < 26 ppm, Sr ~ 160 ppm), most samples yield values more similar to those reported by White and Schilling (1978) for enriched or plume-type MORB from the Azores (Ba > 100 ppm, Sr > 200 ppm).

The chemical data illustrate the primitive nature of HAOT as well as its uniqueness in the northwestern United States. The homogeneous nature of this unit, together with its similarities to oceanic basalts, suggests that HAOT is derived from an upper-mantle source that has undergone significant regional depletion(s). This source region may be similar to that producing MORB and BABB, although the higher concentrations of Sr and Ba in HAOT may indicate that the source is slightly less depleted than typical oceanic mantle.

STRATIGRAPHY AND GEOCHRONOLOGY

Northeastern California

This region lies between approximately 120°W to 122°W long. and 41°N to 42°N lat. in Modoc, Siskiyou, Lassen, and Shasta Counties,

California. Sampling was concentrated in the areas north and west of Alturas and adjacent to Lava Beds National Monument and Medicine Lake (Fig. 2). Stratigraphy is difficult to discern because of low relief and the absence of deeply incised valleys, as well as the fact that so many of the lavas interfinger and overlap in subtle ways. Further difficulties are encountered when attempting to identify the actual vents for HAOT. Scattered buttes, cones, and craters that appear to be centers for young HAOT volcanism are present in small numbers. Most older centers, if present, would be eroded and covered over by younger volcanism. For the most part, HAOT is considered a product of fissure eruptions, which certainly corresponds to the tectonic style of this region.

Published geochronologic studies in this portion of northeastern California are sparse (McKee and Duffield, 1979; Luedke and Lanphere, 1980; Mertzman, 1981; and McKee and others, 1983) and only casually suggest the regional significance of HAOT. Nonetheless, HAOT is by far the most voluminous and widespread unit occurring within this region, covering or underlying at least 8,000 km². This is a conservative estimate, as nearly 3,600 km² of this figure is well documented in the region northwest of Alturas. Using the estimated area of HAOT coverage (~3,600 km²) and an average thickness of 30 m, an approximate volume of 110 km³ is suggested for HAOT in the region northwest of Alturas. Very young (0- to 1-m.y.-old) flows of HAOT are common in the areas adjacent to and north, south, and west of Medicine Lake. Generally, they occur as graben fill and basal flows surrounding both older (1- to 2-m.y.-old) basaltic andesite shields and cones and very young (<100,000-yr.-old) andesite flows associated with the Medicine Lake Volcano (Mertzman, 1981). HAOT flows between 1 and 3 m.y. in age are observed unconformably overlying older, 3- to 5-m.y.-old basaltic andesites exposed along Gillems Bluff, a north-south-trending normal fault scarp extending 25 km along the western border of Lava Beds National Monument. A few large fields of HAOT exhibiting constructive topographic features are present, such as the Giant Crater flows south of Medicine Lake (~250 km²) and the flows north of Tennant (~100 km²).

The data shown in Table 4¹ illustrate both the wide range in time and

¹Tables 4, 5, and 6 may be obtained free of charge by requesting Supplementary Data 84-3 from the GSA Documents Secretary.

Figure 4. MgO-TiO₂-K₂O ternary plot. The fields shown for each group are drawn on the basis of analyses the averages of which are reported in Tables 2 and 3. Fields 1, 2, 3, 4, 5, and 6 represent HAOT, LKLT, LKHT, SROT, AOB, and Steens Mountain, respectively. Individual data points are plotted for the Columbia River basalt group on the basis of categories defined by Swanson and others (1979).

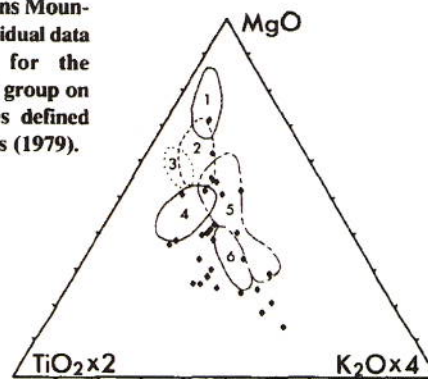


TABLE 3. BASALT COMPARISONS

(n)	HAOT 50	MORB 190	BABB 43	IAT 52	CRPG 8	SROT 96	SM 48	BRAB 36	AV 6	TPS 5
SiO ₂	47.66	49.74	49.32	52.41	50.36	46.68	48.37	48.50	50.83	50.83
TiO ₂	1.00	1.28	1.24	0.85	1.56	2.75	2.29	1.77	1.46	1.18
Al ₂ O ₃	16.91	15.83	16.45	18.73	15.54	15.07	16.01	15.10	14.97	16.25
FeO ¹	9.88	9.28	8.68	9.04	11.25	13.58	12.49	9.54	10.89	10.60
MnO	0.17	0.16	0.18	0.17	0.20	0.20	0.18	0.15	...	0.16
MgO	9.06	8.40	7.93	4.68	6.68	7.53	5.05	7.45	8.63	7.32
CaO	11.20	11.54	11.61	9.99	10.67	10.00	8.78	9.50	9.41	8.94
Na ₂ O	2.53	2.55	2.77	2.97	2.95	2.49	3.48	3.52	2.90	3.01
K ₂ O	0.23	0.18	0.32	0.62	0.57	0.62	1.27	1.48	0.54	0.66
P ₂ O ₅	0.13	0.15	0.15	0.17	0.22	0.58	0.47	0.50	0.21	0.18
MgO/FeO*	0.92	0.91	0.91	0.52	0.59	0.56	0.40	0.78	0.79	0.69

HAOT - from this study; mid-ocean ridge basalt (MORB), back-arc basin basalts (BABB), island arc tholeiites (IAT), Steens Mtn. basalts (SM), and Basin and Range alkaline basalts (BRAB) from compilation in Hart (1982); CRPG - Columbia River High Mg Picture Gorge Basalt, Swanson and others (1979); SROT - Snake River olivine tholeiite, Leeman (1974) and this study; AV - Albuquerque Volcanoes, Table 3 of Baldrige (1979); TPS - Taos Plateau-Servilleta basalt, Lipman (1969), and Lipman and Mehnert (1979).

geographic area occupied by HAOT in northeastern California. A rather irregular age pattern is observed, but, in general, the youngest exposed HAOT flows (<1 m.y. old) are located adjacent to the Medicine Lake Highlands and the oldest (7–9 m.y. old) adjacent to Alturas and along the California–Oregon border (5–8 m.y. old). HAOT of intermediate age (1–5 m.y.) is exposed throughout the remainder of the region. A general eastward increase in age is noted from the available data. Furthermore, it appears that normal faulting associated with HAOT magmatism throughout this region can be as young as 0.5 m.y. and may have occurred sporadically over at least the past 6 m.y. Utilizing an average thickness of only 40 m, a *minimum* volume of 350 km³ is suggested for HAOT magmatism in northeastern California.

Owyhee River–Western Snake River Plain (OR–WSRP)

This region lies between approximately 115°W to 118°W long. and 41°45'N to 43°45'N lat. in southeastern Oregon, northern Nevada, and southwestern Idaho (Fig. 2). Sampling within this 80,000-km² area was concentrated in and around the Owyhee River and the region northwest of Jordan Valley, Oregon. The age data for this region are summarized in Table 5.² Basalts ranging in composition from HAOT to TB, SROT, and AOB and in age from 0 to 10.5 m.y. are observed. It is conservatively estimated that HAOT covers ~8,000 km² of this region with an average thickness of 20 m and a minimum volume of 150 km³.

In southernmost Idaho and Oregon, HAOT flows ranging from 5 to 6.9 m.y. in age unconformably overlie silicic material chemically correlative to the Idavada volcanics. Along the Owyhee River canyon in northern Nevada and southeastern Oregon, similar silicic material is overlain by thick sequences (as much as 200 m) of interbedded transitional tholeiites and red silicic tuff ranging in age from 1.5 to 9.9 m.y. HAOT flows often observed capping these sequences yield ages of 0.9 to 6 m.y. Farther north along the Owyhee River, just south of Owyhee Reservoir, in Oregon, 4.1-m.y.-old HAOT (H-8-45, H-8-47) is interbedded with chalk and lacustrine sediments. Beneath this ~100-m sequence, there is almost 120 m of sediment that in turn is underlain by a 4.5-m.y.-old LKLT flow (H-8-42). The occurrence of widespread lacustrine sedimentation between 4 and 5 m.y. B.P. has been documented for much of the western Snake River Plain region (for example, Glenns Ferry–Chalk Hills Formations; Malde and Powers, 1962; Armstrong and others, 1975). The timing of this sedimentation corresponds with onset of active extension in this region. The possibility thus exists that the major episodes of normal faulting that created grabens in which large lakes formed also created passages for basalt (for example, HAOT) to erupt.

Detailed sampling in the area between the Owyhee River and Jordan Valley, Oregon, indicates that HAOT ranging from 0.4 to 8.5 m.y. in age is closely associated with young (0- to 2-m.y.-old) alkaline basalts, transitional tholeiites (1.1- to 9.9-m.y. old), undated silicic flows and tuffs, and lacustrine sediments (Hart and Mertzman, 1983). The 8.5-m.y.-old HAOT (SM-75-12A) exposed at the base of Jordan Creek is the oldest HAOT flow observed in the Jordan Valley vicinity. The oldest dated HAOT (HSR-5; 10.2 m.y.) from the OR–WSRP region is exposed 60 km north of this location.

The remainder of the samples dated from within the OR–WSRP region are LKLT, LKHT, and SROT lavas exposed in small river cuts or fault scarps. East of the Owyhee Mountains in southwestern Idaho, these samples range from 4 to 10.5 m.y. in age and often are found either interbedded with lacustrine sediments (H-9-13A, H-9-13B) or overlying silicic Idavada material (H-9-15B). West of the Owyhee Mountains, three additional samples of LKLT and LKHT were collected (7.2 to 10 m.y. in age).

Other Geographic Areas

Attention is now turned to the remainder of the study region not previously discussed. It is obvious from Figures 1 and 2 that the samples here encompass a wide geographic area that is characterized by a variety of geologic environments. The complex geologic nature of this region arises from the fact that volcanic sequences from the Cascade, Columbia River, Snake River, and Basin and Range provinces, as well as from the Steens-Pueblo, Owyhee, Jarbidge, Santa Rosa, and Warner Mountains together with the Harney Basin, all interfinger with time-correlative and younger HAOT flows.

On the basis of the present reconnaissance study, combined with some of the previously mentioned work, a conservative estimate of 6,000 km² is suggested for the area of exposed HAOT. Field observations from this study indicate that HAOT commonly ranges from 10 m to 25 m in thickness. This, combined with the area estimate, yields a volume of approximately 125 km³ for HAOT in this region. The majority of this volume has probably been extruded from fissures related to the regional extensional tectonic regime. Scattered cinder cones and eroded vents are also observed (for example, Diamond Craters). Basaltic samples from this region span the entire composition range from HAOT to AOB and extend in age from 0 to 15 m.y. (Table 6).³ HAOT samples vary from 0 to 7 m.y. in age and are seen flowing around and unconformably overlying significantly older basalts (>11-m.y.-old) at Steens Mountain, Polker Jim, and Abert Rims (Hart and Mertzman, 1982).

²See footnote 1.

³See footnote 1.

From the regions northeast and southeast of Winnemucca, Nevada, four samples have been dated, and these range from 3.4 to 5 m.y. in age. Of the four, three (H-8-91, H-8-95, and H-8-96) are HAOTs that occur as thin flows forming mesas in alluvial regions. The area outlined by these three HAOTs defines the southern edge of HAOT occurrence and intercalates with alkaline basalt (AOB) volcanism of similar age (H-8-92).

Three samples from the eastern Steens Mountain region have been examined. In this area, 11.2- to 11.7-m.y.-old flows and high points (H-8-74 and H-9-32) of quartz normative tholeiite chemically and petrographically similar to Steens Mountain Basalt are identified. These are the youngest reported ages for Steens Mountain volcanism and are 3 to 4 m.y. younger than the suggested average of 14.7 to 15.4 m.y. (Baksi and others, 1967). It is suggested that these lavas represent a later-stage basalt eruption genetically related to the bulk of the Steens basalts (Hart and Mertzman, 1982).

Unconformably overlying H-8-74 and H-9-32 are younger HAOT flows. The youngest of these flows, H-8-73, has been dated at 0.43 m.y. B.P. Although not observed in direct contact with the Steens material of this study, a 4.5-m.y.-old LKLT sample is the next oldest material detected between this area and the Owyhee River. The combined field and geochronologic data from this study suggest the presence of a major erosional unconformity between 11 m.y. and 4.5 m.y. B.P. This time period partially coincides with the period of large-scale lacustrine sedimentation previously proposed for this region. The occurrence of small patches of tuffaceous sedimentary material underlying the young, 11 m.y.-old Steens basalts further supports this hypothesis. Walker (1977) reported K-Ar ages of about 9.7 m.y. to 4 m.y. for basalts and ash-flow tuffs interbedded with these sediments. Significant stages of uplift and subsequent graben formation may have allowed for the initiation of such a major lacustrine system(s). If this were the case, it might be expected that erosion postdating uplift created the observed unconformity between 11 m.y. and 4.5 m.y. B.P. The best-exposed and most significant source of HAOT uncovered in this study is at Diamond Craters, Oregon. There, a 100-km² basalt field has its source entirely characterized by central vents in the form of craters and cinder cones. These vents have erupted both cinders and flows. Sample DC-1, which was taken from the wall of one of the craters, yields a maximum age of 0.02 m.y. It appears that this very young HAOT field is underlain by Pleistocene HAOT (for example, H-8-75A).

The remaining samples were collected along the three rims: Abert, Polker Jim, and Egli (Fig. 2). Two occurrences of HAOT are identified in these areas. At Abert Rim, a single flow of 6.1-m.y.-old HAOT (H-9-72) flows around the base of uplifted 14- to 15-m.y.-old basalts. In contrast, 6.85-m.y.-old HAOT is observed on the upthrown side of Polker Jim Rim, overlying a sequence of basalts similar in age and composition to those at Abert Rim. These relationships suggest an age of faulting of between 6 m.y. and 7 m.y. for this region (Hart and Mertzman, 1982). This premise corresponds with the conclusion reached in previous investigations (Ekren and others, 1968) that most of the high-angle faulting around the margins of the Great Basin is Miocene or younger.

Regional Stratigraphy

The late Cenozoic stratigraphic nomenclature for the northwestern Great Basin has developed in piecemeal fashion over the past 50 yr. Individual workers studying isolated areas and/or rock units have derived their own sections and nomenclature, and confusion arises when attempting to correlate these. Much of the confusion is in part due to the fact that many of the sedimentary and volcanic units are of local extent and often are bounded by unconformities. The basalt flows, which dominate the volcanic sequence, were controlled by the local topography onto which

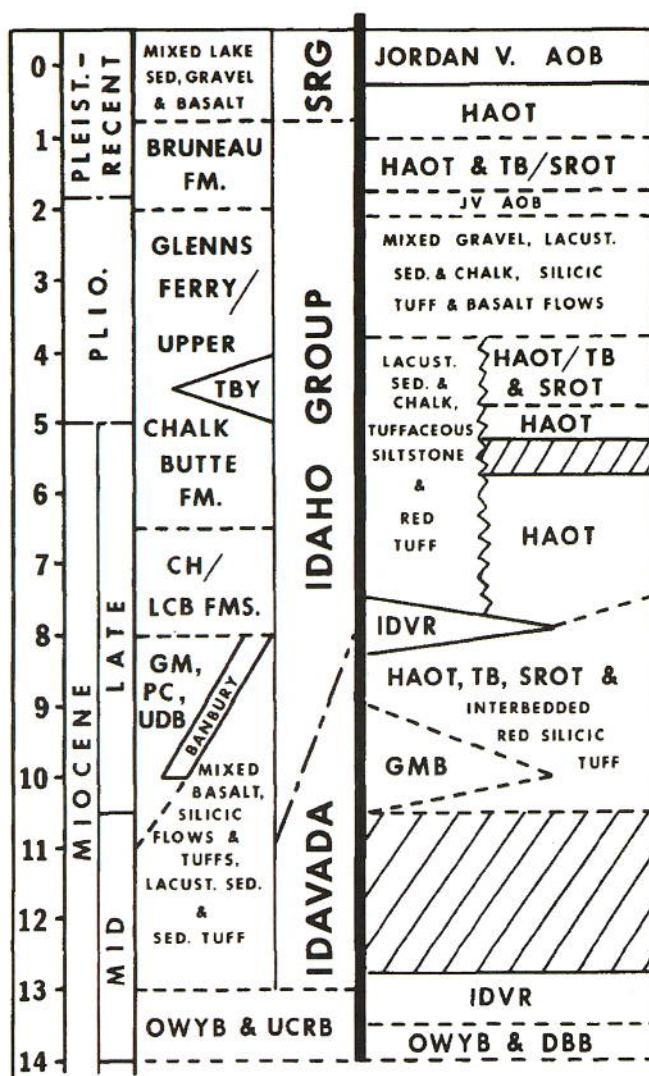


Figure 5. Comparison of generalized Owyhee River–Western Snake River Plain stratigraphy, after Evetts (1979) (left) and from the present study (right). SRG, Snake River Group; TB, Type Banbury Basalt; CH, Chalk Hills; LCB, Lower Chalk Butte; GM, Grassy Mountain Formation; GMB, Grassy Mountain Basalt; PC, Poison Creek Formation; UDB, Upper Deer Butte Formation; DBB, Deer Butte Basalt; IDVR, Idavada Rhyolite; OWYB, Owyhee Basalt; UCRB, Upper Columbia River Basalt. Ages in m.y.

they were extruded, giving rise to features such as local basin and channel-fill sequences. Such characteristics make it very difficult to correlate these sequences across large distances strictly on the basis of field relationships and sample descriptions.

Figure 5 represents a composite stratigraphic column that compares published stratigraphic nomenclature for the OR–WSRP region with the results of this study. It is obvious from this summary that detailed petrographic, chemical, and geochronologic investigations either allow for more precise stratigraphic correlations using established nomenclature or indicate the need to expand and modify the nomenclature in order to arrive at accurate classification. In this particular situation, the data indicate that proper recognition of the chemical differences between the observed basalts together with the correct classification of what we refer to as

HAOT can set the stage for more explicit regional geologic interpretation. With this in mind, we present a summary of the regional stratigraphic importance of HAOT:

1. HAOT magmatism is not time-correlative with the bulk of Columbia Plateau or Steens Mountain magmatism.
2. HAOT magmatism overlaps in both time and stratigraphic occurrence with lavas of the Snake River Plain.
3. HAOT lavas should not be utilized as regional time-stratigraphic markers.
4. HAOT should be treated as a single chemical unit (magma type) that can be used to trace both local and regional stratigraphic and tectonic development throughout the northwestern Great Basin over the past 10 m.y.

In light of these four points, two particular regions of previously poorly interpreted HAOT occurrence warrant further discussion. In northeastern California and the OR-WSRP region, the terms Warner Basalt and Banbury Basalt, respectively, have been utilized to describe a wide range of volcanic material, including HAOT.

In northeastern California, the term Warner Basalt was originally adopted by Russell (1928) to describe basalts exposed throughout Modoc County and the Warner Range as well as basalts extending northward to the Warner Valley and Abert Rim, Oregon, and eastward to Steens Mountain, Oregon. Many of these correlations were based on the work of Merriam (1910), which suggested that the basalts exposed throughout this entire region represent a single flood basalt sheet. Wheeler and Coombs (1967) pursued this suggestion and proposed that all of the locally named basalts exposed east of the Cascades and south of the Columbia Plateau throughout northeastern California, northern Nevada, central and eastern Oregon, and south-central Washington (including the "Warner Basalt") actually constituted a single flow erupted during the latest Pliocene or early Pleistocene ("Mesa Basalt"). Walker and Swanson (1969) were the first to argue that the existence of such a widespread single flow was impossible, on the basis of regional stratigraphic and geochronologic evidence. The data and observations reported in this study further substantiate Walker and Swanson's conclusions.

The notion of a single flood-basalt sheet dispelled, we are still left with the Warner Basalt enigma. Powers (1932), in his study of the lavas of the Modoc-Lava Beds area, and Anderson (1941), in his work around the Medicine Lake Volcano, both utilized the term Warner Basalt in accordance with Russell's original interpretations. Judging from these descriptions, the unit most commonly referred to as Warner is petrographically and chemically identical to the HAOT of this study. However, many occurrences of material best correlated with the Cedarville Series (Powers, 1932) and the Medicine Lake-Lava Beds volcanic sequences (Mertzman, 1977a, 1977b) have also been historically assigned the name Warner Basalt. An excellent example of this is noted in the exposures along Gillems Bluff, west of Tule Lake, where Powers (1932) describes a 130-ft vertical section of 12 separate Warner Basalt flows. On the basis of petrographic and chemical analyses of material from various locations along this fault scarp, we suggest that a significant amount of this material is andesitic, correlating well with the lavas emanating from Mount Dome, an andesitic composite volcano nearly 15 km to the southwest. Along the northwestern edge of Lava Beds National Monument, this andesite is unconformably overlain by HAOT. Similarly, the HAOT age data combined with the 15-m.y. to 32-m.y. age range (Duffield and McKee, 1974) and observed chemical characteristics of the volcanics in the Warner Mountains indicate that the term Warner Basalt should not be utilized to describe basalts within this sequence.

Due primarily to its confusing history and occasional incorrect usage,

we believe that the term Warner Basalt should be completely abandoned. We suggest that in this situation, where a unique chemical unit can be traced over a wide geographic area and over a wide absolute time span (0–10 m.y. B.P.), that the chemical name should be employed. Thus, usage of the name low-K, high-alumina olivine tholeiite (HAOT) not only yields important descriptive information, but also minimizes the problems derived from local stratigraphic nomenclature.

In the OR-WSRP region, the term "Banbury Basalt" has been used to define both 4- to 5-m.y.-old and 8- to 10-m.y.-old basalts (Fig. 5). The free usage of this name throughout the literature dealing with this region is one of the most confusing of the nomenclature problems. The Banbury Formation was originally named by Stearns (1936) and formalized by Malde and Powers (1962) to include exposures of basalt and sandy tuffaceous sediments at Banbury Hot Springs on the Snake River in Elmore County, Idaho. Ages of between 4.4 and 4.9 m.y. were reported by Armstrong and others (1975) for this type section. Unfortunately, Malde and Powers and many subsequent investigators extended this name to include other olivine basalts throughout the OR-WSRP region that are both chemically and geochronologically *dissimilar* to the type section. Stewart and Carlson (1976) indicated a large tongue of "Banbury" extending into northern Nevada, and McKee and Mark (1971) and Mark and others (1975) proposed that olivine tholeiites from this region define a southern distal edge of the Snake River Plain province. Extensive chemical and petrographic analyses from the present study indicate that much of the Banbury Basalt (excluding the type locality) is actually low-K, high-alumina olivine tholeiite (HAOT) and should not be genetically correlated with the bulk of the Snake River olivine tholeiites. In fact, the chemical data suggest that there is a chemical continuum of basalt in the OR-WSRP region from low-K, high-alumina olivine tholeiite to olivine tholeiites of the Snake River Plain (including the type Banbury Basalt), with a wide array of basalts compositionally intermediate to these end members. Such chemical complexity implies that terms such as "Banbury Basalt" should either be abandoned or used strictly to describe a type section and other sections or flows directly correlatable on the basis of age, stratigraphic occurrence, and chemistry. This same reasoning should be applied to other basalts and basalt formations in this region. In Figure 5, the use of chemical names in identifying basalt sequences is emphasized to illustrate the time-transgressive nature of this volcanism. Utilization of this type of chemical classification combined with established nomenclature and additional geochronology should clear up many of the existing ambiguities. One final caution: the reader should not confuse geochronologically defined stratigraphic horizons with sequences of a particular magma type or chemical group. At the same time, the reader should recognize that magmas of very similar composition have erupted over a 0- to 10.5-m.y. span in the OR-WSRP region (for example, HAOT).

DISCUSSION

HAOT is a significant volcanic unit of the northwestern Great Basin that should be incorporated into discussions of the volcano-tectonic history of this region. Figure 6 summarizes the age data for surface samples from this study and delineates the region of observed HAOT occurrence. No significant regional age patterns can be gleaned from the data because the entire measured age range (0–10.5 m.y. B.P.) is observed in HAOTs from both the eastern and western margins of the outcrop area. Nevertheless, the lack of sampled HAOT older than 7 m.y. in the central portion of this region may indicate regional differences in the tectonics and/or upper-mantle processes acting on this region from 7 to 10.5 m.y. B.P. The ~10-m.y. ages can be correlated with the age of inception of basaltic

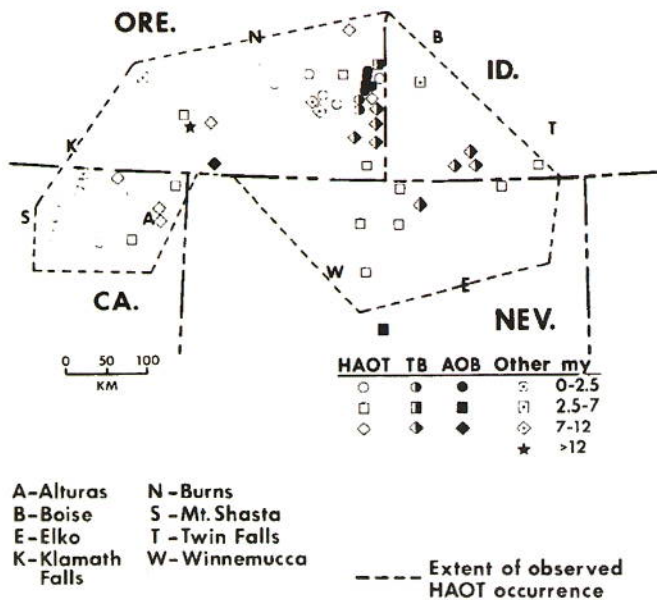


Figure 6. Summary of surface age and composition distribution of northwestern Great Basin basalts.

volcanism in the western Snake River Plain (Armstrong and others, 1975), whereas the 7-m.y. age may mark the inception of major late Cenozoic tectonism in the extreme northwestern Great Basin.

It is conservatively estimated that HAOT covers at least 22,000 km² of the region enclosed in Figure 6. This estimate, combined with observed thicknesses, suggests a minimum volume of 650 km³ for this magma type. Although minor in comparison to Columbia River, Steens Mountain, and Snake River Basalts, for example, less than 1% of the estimated volume of Columbia River Basalt (2×10^5 km³; Swanson and Wright, 1978), this volume (~650 km³) is still sufficiently large to warrant careful consideration of the role of HAOT in the evolution of the northwestern Great Basin.

The age data from this study suggest that three important pulses of magmatism occurred in the northwestern Great Basin during the late Cenozoic; at 0–2.5 m.y., 3.5–6 m.y., and 7–10 m.y. B.P. (Fig. 7). A fourth pulse at 13–16 m.y. B.P. is also suggested from only limited data. The three younger magmatic episodes are well defined by HAOT alone, and it is probable that with further sampling the 13–16-m.y. pulse would be better defined, because this is the age range for the bulk of the Columbia River and Steens Mountain volcanism. The four periods noted above agree well with the episodes delineated from ash abundances in Deep Sea Drilling Project (DSDP) cores from the entire circum-Pacific region (Kennett and others, 1977).

Episodic volcanism, such as that documented in the northwestern

Great Basin and in the circum-Pacific region in general, records fundamental tectonic changes relating to changes in the rate of sea-floor spreading and subduction. An example of this suggested correlation is observed in volcanics of the Basin and Range province (McKee and others, 1970). A hiatus in volcanism occurred between 17 and 20 m.y. B.P. This volcanic lull correlates with the inception of crustal rifting and Basin and Range faulting (Dott, 1969), the intersection of North America with the East Pacific Rise, subsequent destruction of portions of the ridge, and initiation of the San Andreas transform fault system (Christiansen and Lipman, 1972). Furthermore, evidence from ash-flow units in the central Great Basin indicates that this region was characterized by generally flat topography prior to 20 m.y. B.P., thus suggesting that most Basin and Range faulting has taken place since the resumption of volcanism at ~17 m.y. B.P. (McKee and others, 1970). Voluminous late Miocene and Pliocene lacustrine sedimentation in the northwestern Great Basin most likely relates to the formation of basin structures, which further substantiates the suggested timing of most intense faulting.

Assuming that the late Cenozoic volcanism in the northwestern Great Basin is intricately related in both space and time to the tectonic changes taking place along the North American plate margin, we propose that a period of major mantle upwelling began at about 14 m.y. B.P. in the extreme northwestern Great Basin. Both the inception and continuation of this upwelling seem to be accurately recorded by the rhyolitic volcanism (Christiansen and McKee, 1978). Subsequent crustal thinning and rifting by 10 m.y. B.P. allowed the first HAOT magma to reach the surface in southeastern Oregon and northeastern California. At present, these two 10-m.y.-old HAOT locations are separated by ~200 km, a figure that agrees with the previously discussed estimates for total crustal extension in this region. The fact that these figures agree is not simple proof of the proposed 200 km of extension because pre-existing rocks produced by magmatism between 13 and 16 m.y. B.P. occur in the region in between (for example, Steens Mountain, Polker Jim, and Abert Rims). More likely, the 10-m.y.-old HAOT occurs at the extremities of the HAOT distribution, because these two areas are located over the previously active tectonic regions of the Cascades and western Snake River Plain. In such weakened regions, corridors for magma ascent would have had a better chance of breaking through the crust during initial mantle upwelling, crustal thinning, and extension. This correlation between recent volcanism and tectonism and ancient tectonic features was suggested by Christiansen and McKee (1978) as having played a major role in the formation of the northwestern Basin and Range.

By about 7 m.y. B.P., the high-angle normal faulting associated with extension in the Basin and Range province became an important tectonic factor in the southern Oregon portion of the northwestern Great Basin. The increased tectonic activity allowed HAOT to reach the surface throughout this region. Such a migration of both tectonism and magmatism toward the edges of the Basin and Range province with time has been discussed by many researchers (see Christiansen and McKee, 1978, for summary). General east-west extension has continued to the present

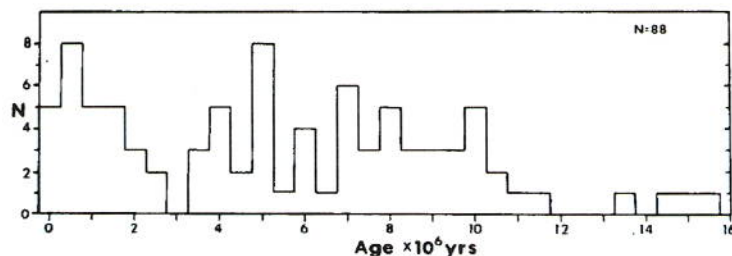


Figure 7. Histogram of K-Ar data for the basalts of this study.

throughout the northwestern Great Basin and is recorded by the HAOT magmatism.

Geophysical data indicate that the entire northwestern Great Basin is characterized by thin crust (25–35 km), high heat flow (1.5–3.0 HFU), and Pn velocities in the range of 7.8 to 7.9 km/s (see summaries and references in Hill, 1978, and Smith, 1978). These characteristics may indicate that the upper mantle beneath this region is anomalously hot.

Scholz and others (1971) suggested that the entire Great Basin may actually represent an ensialic back-arc basin. We believe that the striking geochemical similarities between HAOT and back-arc basin basalts, combined with the HAOT age data and the available geophysical data, support this general hypothesis. Although we are not suggesting that the entire region of this study is underlain by 0- to 10-m.y.-old HAOT, we do think that processes similar to those of typical circum-Pacific back-arc basins have acted on the region behind the southern Cascade arc, thus allowing, after initial melting and thinning of the continental crust, eruption of depleted, oceanic-type basalt (HAOT) in significant volumes over the past 10.5 m.y. Furthermore, the geographic limits of HAOT volcanism may be reflecting the combined influences of active extension and of possible regional age and compositional variations in both the crust and upper mantle. For example, the eastern boundary of HAOT occurrence approximately coincides with the proposed edge of pC continental crust in this region (Armstrong and others, 1977). In fact, no pC material has been observed within the region enclosed in Figure 5. Similarly, ancient (2.7 B.Y.?) chemically evolved subcontinental lithospheric mantle may exist beneath the western Snake River Plain (Leeman, 1974). If this type of material exists beneath other regions in the northwestern United States, it may eliminate the potential for oceanic-type tholeiitic magmatism to occur. This argument is especially compelling if we consider tholeiitic magma generation to be a rather shallow process (~30 km) (Gast, 1968; Presnall and others, 1979). In the northwestern Great Basin, depleted oceanic-type upper mantle combined with large-scale extensional tectonism together yields the observed low-K, high-alumina olivine tholeiite magmatism.

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APPENDIX: K-Ar ANALYTICAL METHODS

Special care was taken to choose fresh samples whenever possible. In all cases, whole-rock samples were analyzed. Each sample was crushed to between 8 and 45 mesh and ultrasonically washed in deionized H₂O and methanol before removal of aliquots for argon and potassium analyses.

All argon analyses were performed at Case Western Reserve University utilizing an on-line extraction system which can be baked out. Before argon extraction, all samples underwent a 10- to 16-hr bake-out at temperatures between 200 and 250 °C. After baking, samples were fused by heating with an induction furnace to between 1,200 and 1,500 °C. Known amounts of pipetted ³⁸Ar tracer were added to the evolving gases

before maximum fusion temperature was reached. During fusion, volatile gases were collected by titanium metal heated to a maximum of 800 °C. Final cleanup was done with a titanium getter. The gas was analyzed on an MS-10 mass spectrometer operated in the static mode. The mass spectrometer was corrected for discrimination by the measurement of atmospheric ⁴⁰Ar/³⁶Ar every three to six sample runs.

The K₂O values reported in this study were measured by either flame photometer, X-ray fluorescence, isotope dilution, or a combination of these techniques. Various aliquots were analyzed, and the different techniques and aliquots yielded comparable values. In cases of discrepancies, the flame-photometer value taken from the same aliquot utilized for argon analysis was utilized.

The uncertainty in calculated ages was estimated by assuming (1) a 0.3% uncertainty in the measured isotopic compositions of sample and atmospheric argon, (2) a 1.0% uncertainty in the volume of the ³⁸Ar spike (tracer), (3) a 2.0% uncertainty in sample homogeneity, and (4) an absolute uncertainty in the measurement of potassium. For samples with K₂O > 1.0 wt %, a 1.0% uncertainty was assumed, and for samples with K₂O < 1.0 wt %, the error was assumed to be an absolute amount of ±0.01 wt % K₂O.

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